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Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
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The American Association of Petroleum Geologists

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Journal of Sedimentary Petrology

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Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 17, NO. 1, PP. 3–7
FIG. 1, APRIL, 1947

CORRELATION BETWEEN ALLOGENIC GRADE SIZE AND ALLOGENIC FREQUENCY IN SEDIMENTS

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ABSTRACT

Working-hypotheses regarding the interpretation of allogenic grade size-frequency correlations are presented and applied to certain petrographical data.

In a previous paper (1945), certain criteria were suggested by which the mutual and separate transport, and therefore provenance, of some detrital minerals may be recognized by their grade size-frequency correlations. Since then, a number of sedimentary petrologists have expressed their opinion that further amplification of these ideas—however tentative—would be useful in the development of the subject, particularly in its experimental and mathematical aspects. Despite the frequently inconclusive nature of the matter, therefore, and its overall lack of philosophical tidiness, the following account of the author's contemporary working-hypotheses is presented in the hope that their opinions may be justified.

MAJOR CAUSES OF ALLOGENIC GRADE SIZE-FREQUENCY CORRELATIONS

Correlations between allogenic frequency (number-percentage) and grade arise in a variety of ways.* They may become established (1) in any basin of deposition, and among any species, by limitations of particle size at source, by decomposition, grain breakage and by sorting ("unrestricted transport"); and (2) in basins of deposition receiving sediment from a variety of drainage-systems, by restrictions in the supply of certain species to one, or an unrepresentative few, of these ("restricted transport"). Such mechanisms have certain consequences which prove useful in the interpretation of sedimentary correlations. Their theoretical examination is based here on one major premise,—that during the periods of time represented by the smallest possible thicknesses of rock which can be sampled, influent rivers normally contributed detritus graded according to peaked size-distributions.

* In an important paper lately received, B. Brajnikov (1944) strongly emphasizes the rôle of particle size in determining sedimentary compositions.

UNRESTRICTED TRANSPORT

Several Drainage-Systems. Minerals carried by all or most of a variety of drainage-systems will generally originate from a number of different sources, and present no systematic limitations of size at the site of deposition. They will normally comprise the commoner members of source-complexes, and fluctuate in amount more or less independently of grade size within the final sediment.

If limitations are imposed at source upon the size-range of a species (whether its source be primary or secondary) they must become reflected within the ultimate deposit. In this way grade size-frequency correlations may be set up, but they will always be low,—indeed often non-existent,—owing to the petrological heterogeneity of most geographical hinterlands. Examples, however, are familiar to all sedimentologists. The widespread decline of heavy detritals in the coarser grades is well known, and this universal tendency towards a low negative regression of "heavy" frequency upon grade doubtless results from the world-wide restrictions in size imposed upon the familiar "heavy" crystals of most pri-

mary sources. Further examples may be expected to arise within sediments formed by the weathering of extensive metamorphic and igneous terrains, and also within certain secondarily derived sediments.

During transportation, breakage of the particles initiates movement towards the finer grades. Its effect will be most apparent at the extremes,—depletion in the coarse and accumulation in the fine. Between the two extremes, the change (?linear) should be liable to some modification (?curvilinear) by the readier breakage of larger particles. Despite this, however, any correlations resulting among the commoner species will be drastically reduced by the physical characters of the minerals, and strictly limited to certain physical types. Tourmaline, for instance, breaks up easily, and its passage into the finer grades can often be traced by parallel changes in abundance. Sometimes, too, this change is detectable vertically into derived sediments.

Geochemical decomposition of sedimentary detritus tends to remove the smaller grains first, and positive correlations are set up. They are recognized by their confinement to the less stable species. Occasionally, rocks bear clay fractions which protect these species, and the resulting localization of decomposition to the coarser facies may generate negative correlations. In both cases, the notoriously fickle nature of geochemistry seems likely to render all such correlations very low in magnitude.

Specifically selective sorting by currents, especially during the depositional phase, is well known to be capable of effecting local transfers from one grade to another. Since there is every reason to suspect that this normally occurs throughout the grade size range, only the extremes are likely to show marked changes of abundance. The resulting correlations in the final deposit will therefore be low in magnitude and positive or negative according as the movement is towards the coarser or finer facies respectively. During such sorting, grain-shape appears to play a key rôle. Its effect is well seen in the high concentrations of muscovite flakes (often ubiquitously derived) so frequently encountered among the finest facies of sediments.

One Drainage-System Only. For reasons similar to those advanced, sediments carried wholly by a single drainage-system, or by systems of equal competence, will also be expected to yield low correlations, or none at all. High correlations at source, however, should have greater chances of survival, for they will be more likely to originate in petrologically homogeneous domains. Additional characters must be invoked for their recognition.

To summarize: detrital minerals supplied from all possible quarters must almost certainly yield either no grade size-frequency correlations, or correlations characterized by

(1) their low magnitude,
(2) their limitation to the commoner species,
(3) their limitation to particular physical and geochemical types,
(4) their particular signs.

RESTRICTED TRANSPORT

Minerals which are carried by one or an unrepresentative few among a *variety* of drainage-systems, will usually possess serious limitations of particle size at the site of deposition. They should therefore show high grade size-frequency correlations,* and since their restricted carriage will result from the localization of their sources, they should generally constitute the less common species of source-rocks. Though recognisable with fair certainty, therefore, they are always liable to confusion with the cases of high correlation occasionally established after conditions of unrestricted transport.

Accepting this possibility as inescapable for the time being, we will enquire into the *relative* characteristics of the cor-

* Either apparently linear, or curvilinear for the regression of frequency on grade. Allogenic correlations curvilinear for grade-on-frequency are inconceivable.

relations. Progress is naturally difficult in the case of sediments with only one restricted species, but as the number increases so the reliability of their interpretation improves. They are most conveniently considered under two headings: (1) those which travelled separately (and probably came from different sources), and (2) those which travelled together (and probably came from similar sources).

Separate Transport. Unless some of the contributory drainage-systems have exactly equal degrees of competence (which is unlikely) the minerals peculiar to each will possess peak-sizes and ranges of size which are neither similar nor hydraulically equivalent. Consequently their sampling data will yield non-coincident regression lines arranged in no particular order along the grade size variable, and this sequence will only fortuitously bear any resemblance to the specific mean size order of the component samples. Nor will the fluctuations in the correlations over space or time reveal anything more than fortuitous harmony,—except in so far as some interspecific mixing may cause localized and clearly defined depressions of frequency. Among these species, too, those emitted by the major inlet will always stand out by attaining their maximum frequencies in the most frequent grades (e.g. garnet, compared with staurolite; figs. 3 and 4, Allen, 1945), and the status of the rest will be revealed by subsidiary peaks and mixing phenomena. In general, correlates of the present type will be genetically diverse.

Mutual Transport. Minerals which travelled together, on the other hand, must (in the absence of other factors) become distributed so as to reach their highest and lowest frequencies in facies of similar grade.* Their regression lines must therefore either coincide (similar frequencies supplied) or be displaced merely in the direction of the frequency-variable (dissimilar frequencies supplied). Such correlations may be termed 'size-coincident.' They will often involve genetically related species. In the special case where the regressions of frequency-on-grade are curvilinear and not widely different in symmetry (e.g. garnet and apatite, fig. 1), those for grade-on-frequency will be practically coincident.

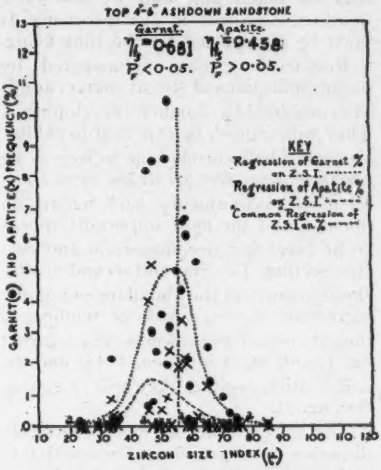

FIG. 1.—Curvilinear correlations between allogenic heavy grade (measured as the zircon size index) and the proportions of garnet and apatite (measured as percentages by number) in the allogenic heavy suite of a stratum 700 sq. miles in extent and 2 inches in thickness.
η_{f_0}=correlation ratio for the regression of frequency on grade and P_F=its significance estimated by the analysis of variance (Fisher, p. 250) and use of the F-test. The values of η_{f_0} given are for 10μ arrays.

Chief among the factors which *tend* to disperse these otherwise 'size-coincident' correlations is limitation of particle size at source. If the source is primary, then they may become scattered parallel to the size-axis in very nearly the same order of magnitude as their primitive crystallographic sizes, and bear no necessary relation to the mean size order of single samples. Fortunately, the real

* Normally implying the *same* facies. They are thus distinguished from minerals which travelled separately, but in drainage-systems of equal competence (above), for these, though attaining their maximum and minimum frequencies in facies of *similar* grade, will not necessarily accomplish this in the *same* localities.

nature of such a sequence is sometimes recognizable,—e.g. when generalizations can be formulated regarding the primitive crystallographic sizes of igneous and metamorphic rocks. If the source is secondary, however, almost any sequence may be taken up,—and we encounter another 'loose end' in our theorizing. It must be disregarded for the time being.

Restricted species, unhampered by major limitations of size at source, admit of considerably further development. They will, indeed, be expected to exhibit size-coincident correlations *so long as no specifically selective agents act upon them.* In most environments, such agents do operate, and the more important appear to be breakage, decomposition and current-sorting. The first and second modify the symmetry of the abundance-on-grade regression curves, breakage tending to impart negative skewness (e.g. garnet fig. 1; and fig. 3 in Allen, 1945) and decomposition positive skewness (e.g. apatite, fig. 1).

The third agent far more effectively disperses the regressions. Irrespective of their original size-distributions at source, the species will at some stage before deposition form a 'hydraulically equivalent' group (such as is found subsequently in small samples) size-graded to achieve equilibrium with the surrounding medium. The possible repercussions of this "hydraulic size order" under various conditions of sorting are deducible with some degree of confidence. Only the simplest (and the commonest?) will be considered here, *viz.* that which passes down essentially unchanged into the sediment finally deposited.

Actively sorting currents operate through selective deposition and/or selective transfer, their predilections being variously determined by particle shape, size, weight or a combination of these, according to circumstances. There is, therefore, no fixed and immutable hydraulic size order for sedimentary minerals. In considering the consequences of this, we shall find it convenient to group detrital minerals according to the above characters, and to consider each group separately. Such a classification has the advantage of a twofold basis, as each character is largely determined by the other two. Four groups are possible, *viz.* those comprising species with (i) similar shapes and similar densities, (ii) similar shapes and different densities, (iii) similar densities and different shapes, and (iv) different shapes and different densities. Their otherwise 'size-coincident' correlations seem most probably to be affected by shape-, size- and weight-sorting in the following ways:

(i) *Similar shapes and similar densities.* No change.

(ii) *Similar shapes and different densities.* While shape- and weight-sorting must usually fail to separate the correlations along the direction of the size-variable, size-sorting may initiate transfer of the denser (finer grained) species towards relatively finer grades, and of the less dense towards the coarser. These movements, having the same trend as the original hydraulic size order, will tend to accentuate it, and—owing to its preservation in the final sediment—will always be small. Their most obvious (and peculiarly diagnostic) effect will therefore be to disperse the regressions so that *the grades in which the species attain their maximum frequencies will fall into the same order of magnitude as that of specific mean size finally established nearly everywhere in the basin.*

(iii) *Similar densities and different shapes.* By analogous considerations, the sequence assumed by the dispersed regression lines will be variously related to the final hydraulic size order as follows: shape-sorting,—reverse; size-sorting,—similar; weight-sorting,—similar.

(iv) *Different shapes and different densities.* For the sake of simplicity, particle shape will be differentiated in this group merely as 'flaky' or 'non-flaky,' and density as 'denser' or 'less dense.' Two subgroups are therefore to be treated—that in which the 'flaky' species are the 'less dense' and that in which they are the 'denser.' The sequences into which their

correlations are likely to be dispersed by current-sorting will be related to the final mean size order as follows: shape-sorting, —reverse (flaky and less dense) or indeterminable (flaky and denser); size-sorting,—similar (flaky and less dense, and flaky and denser); weight-sorting,—indeterminable (flaky and less dense) or similar (flaky and denser).

From the above it will be readily appreciated that the simultaneous or consecutive action of most of the possible combinations of the three postulated types of sorting (taken in pairs or in triplets) will frequently tend to reduce, or even to cancel out, their dispersive powers on the correlations.

SUMMARY AND EXEMPLIFICATION

The possible immediate utility of the present reflections may be suggested by applying them to the petrographical data (Ashdown, Lower Cretaceous) alluded to before (Allen, 1945). Areally within the Ashdown rocks, five species,—garnet, apatite, staurolite, kyanite and sillimanite,—show high grade size-frequency correlations. Their grain sizes normally assume that order of ascending magnitude, the last three form the flakier grains and their regression lines are dispersed into two 'size-coincident' groups:

Garnet	Staurolite
Apatite	Kyanite
	Sillimanite

These groups are so widely separated (see e.g. garnet and staurolite, figs. 3 and 4, Allen, 1945) that the species of the second attain their maximum frequencies in very much higher grades than the rest.

Clearly, restricted transport seems to have been a major cause, the minerals of each grouping, at least, having presumably travelled together. And their petrogenetical relationships corroborate this to some extent. But were all the species transported together, or did the groups travel separately? It is seen that the correlations of the two groups are *widely* dispersed. Their mutual travel seems therefore to be out of the question. Further, it is observed that within each group (similar particle shapes and different densities), only *shape-* or *weight*-sorting would be likely to permit the survival of their regressional coincidences. But only *size*-sorting could conceivably separate the two groups from a hydrulic series like that found in the constituent samples. for their shapes and densities differ widely. Shape- and size-sorting being sharply antagonistic, separate transport is the more likely possibility. This conclusion is supported by the remaining geological evidence.

As a final exercise, it should be noted that the garnet-apatite-bearing river was the dominant contributor to the area sampled, for these species reach their maximum frequencies in the most frequent grades. Surprisingly enough, closely similar conditions were repeated long subsequently (Allen, 1946).

Terms such as "likely" and "seems" occur far too often in the above. We know too little of the intimacies of modern sedimentation, and facts of practical interpretative value are still hard to come by. Only observation and experiment on present-day sedimentation, *carried out with the limitations of the older deposits in view*, can remedy this. Is it too much to hope that during the next few years a team of workers will tackle a complete any distinctive drainage-system, from start to finish?

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 17, NO. 1, PP. 8–17
FIG. 1, APRIL, 1947

HEAVY RESIDUES OF SOILS FROM THE LOWER ORD RIVER VALLEY, WESTERN AUSTRALIA*

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ABSTRACT

The heavy detrital minerals in several types of alluvial soil and one soil derived from the disintegration of sandstones are described, and their value as indicators of the source material of the alluvium discussed.

INTRODUCTION

In 1944 investigations were undertaken by the Government of Western Australia to assess the nature and agricultural value of some 135 square miles of flat plain country in the lower valley of the Ord River about forty to fifty miles from Wyndham (see fig. 1) in the Kimberley Division of Western Australia. It had been suggested that this area might be suitable for irrigation which would encourage closer settlement. The following mineralogical notes formed part of the soil investigations.

The Ord and its tributaries drain about 20,000 square miles of country in Western Australia and a considerable area in the adjoining Northern Territory. The Ord passes through a steep-sided valley some 70 miles from its mouth, and the northern end of this valley has been tentatively selected as the site for a dam from which water will be reticulated to the plain for irrigation. This plain is composed of gray clayey soils, known locally as "black soil plains," which are of alluvial origin, although they very closely resemble soils which elsewhere are known to be derived from basalt or limestone.

Geologically the proposed irrigation area consists of a large flat alluvial plain bounded on its southern and eastern sides by hills of Devonian sandstones, and underlain at some depth by Cambrian basalt and limestone. To the west there is a complex of Pre-Cambrian schists and quartzites. At the site of the proposed dam there is a horst of Pre-Cambrian phyllites and quartzites through which the Ord has cut a gorge 10 miles long.

Physiographically, the drainage basin of the Ord can be divided into two main parts: the upper dissected plateau region; and the flood-plains nearer the mouth.

THE SOILS

A consideration of the development of the Ord River system serves to explain the origin of the soils. The Ord probably at one time flowed east into another river and thence to the sea in a north-north-easterly direction (Burvill). Uplift occurred which dammed up the outlet into this river, and a large swamp or lagoon resulted from the accumulation of the Ord drainage waters which were unable to get away. This uplift also resulted in the rejuvenation of the drainage system in the vicinity of Wyndham, and a small river was able to cut back to the original Ord. This river took the flood waters which had been only able to accumulate, and in addition cut down into the alluvium which had formed by the floodings. The surface became dry land, and the old alluvium was subjected to soil-forming processes. The Ord has now deposited additional alluvial material on its banks above the eroded older alluvium.

The soils occurring in the area were surveyed in detail, mapped, and named in accordance with the recognized princi-

* Published by permission of the Director, Government Mineralogical and Chemical Laboratories, Perth, Western Australia.

ples (Burvill, Teakle). There are three main types of soil:—gray clay soils of the plain; red soils associated with the present alluvial deposits of the Ord; and yellow sandy soils derived from the disintegration of Devonian sandstones. Table 1 gives a summary of the named soils of the area.

TABLE 1

Soil	Color	Origin
Cununurra Clay	Gray or black	Older alluvium
Mantinea Clay	Gray or black	Older alluvium
Ord Sandy Loam	Red	Present day alluvium
Meruin Sandy Loam	Red	Occurs between the Ord Sandy Loam and Cununurra Clay
Junction Complex		Occurs between the Cununurra Clay and Cockatoo Sand
Cockatoo Sand	Yellow	Disintegration of sandstones

The Cununurra Clay and the Mantinea Clay are very similar, and profile samples examined show that they have the following mechanical composition (International Soil Standards):

	Conunurra Clay	Mantinea Clay
Depth	to 138"	to 102"
Coarse sand	1%	.1%–.2
Fine sand	15–17	11–17
Silt	14–30	25–31
Clay	47–60	53–54

The Ord Sandy Loam and the Meruin Sandy Loam are, as their names imply, much more sandy and contain variable amounts of each grading generally with the maximum in the fine sand fraction, which in two samples of Ord Sandy Loam is 54–70 per cent and 66–75 per cent, respectively, at different depths down to 84 and 96 inches. An analysis of the Cockatoo Sand, according to the Wentworth Scale, is given later in the paper.

MINERALOGICAL EXAMINATION

Method. The soils were passed through a 2 mm. sieve and the clay was washed out of the fine earth, dilute NaOH being used to ensure that deflocculation was complete. The dried fine sand was then sieved into two further grades one of which approximated to the fine sand fraction and the other to coarse silt. In some samples only the fine sand was separated in bromoform (S.G. 2.8) to obtain the heavy residue, but in others both the fine sand and silt grades, were used. Where there was very little sand of either grade, as in the Cununurra Clay, the fine sand and silt were not sieved, the total sand being separated in bromoform. Inspection of the mineral grains showed that treatment with acid was not necessary as the grains were free from ferruginous coatings.

In the discussion of results, the heavy residue is expressed as a percentage of the silt grade, and is not the total heavy residue of the sand fraction of the soils. Because of the nature of the alluvial soils, there is a variation in heavy mineral content, due to sedimentation processes, in the various grades. The silt grade was found to yield an abundance of heavy minerals, and in view of Russell's work on the minerals in the Mississippi sands, was adopted here. The relationship of heavy mineral content to grade size is illustrated in table 2.

Heavy Residues. The fine sand and silt grades of the Ord River Valley soils contain a great variety of heavy minerals. This variety was unexpected, because gray soils in this part of the Kimberleys have generally been thought to be derived from basalt and limestone. There is some difficulty experienced in geological and soil mapping where there are no out-

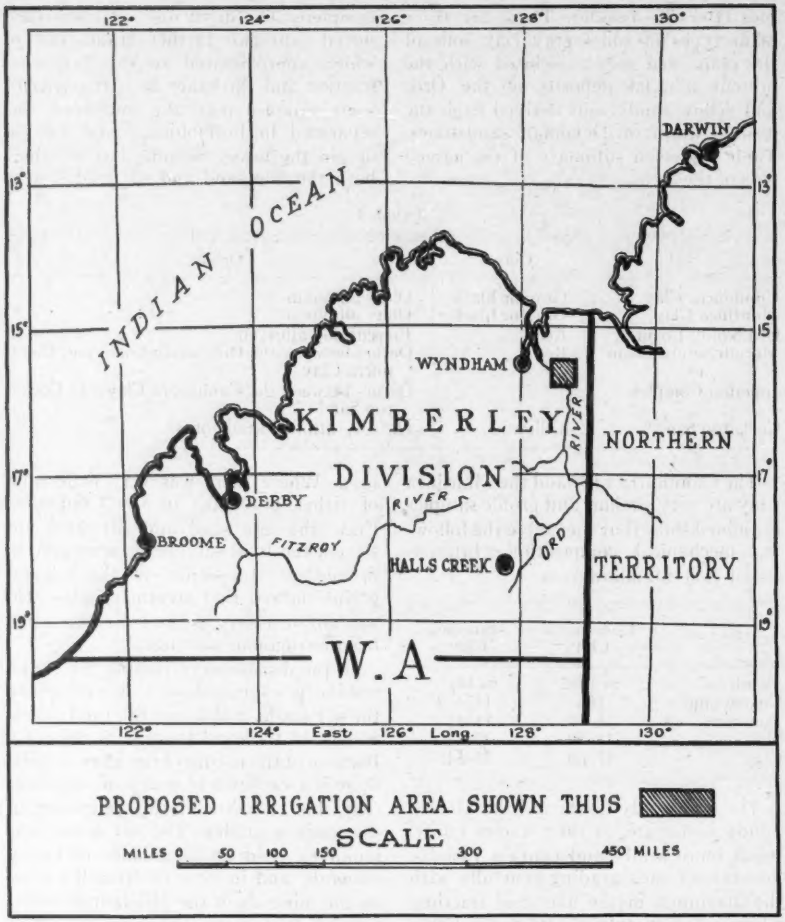

FIG. 1.—Northern portion of western Australia.

crops owing to the similarity in appearance of gray soils derived from basalt, limestone, or of alluvial origin. The most recent geological map (Matheson and Teichert), in fact, implies that the gray Cununurra Clay, recognized by the soil surveyors as alluvial, is derived from basalt, whereas in actual fact it is of very mixed parentage as the heavy detrital minerals show.

The minerals identified in the heavy residues are: amphiboles, anatase, andalusite, apatite, chlorite, corundum, epidote, garnet, glaucophane, hypersthene, (?) iddingsite, ilmenite, limonite, magnetite, mica (biotite), monazite, pyroxene, rutile, serpentine, sillimanite, sphene, staurolite, tourmaline, zircon, zoisite.

Certain mineralogical features of significance with regard to the soils of this

area are worth mentioning before describing the residues from the soil types:—

1). In the clay soils (Cununurra Clay, Mantinea Clay) there is not the usual variation with depth whereby the quantity of residual minerals decreases as the kaolinized parent rock is reached (a cubic foot of surface soil derived from a granite, for example, represents much more than a cubic foot of parent rock and therefore will contain a greater proportion of resistant accessory minerals of diagnostic significance).

2). A certain amount of banding is evident in these soils caused by sedimentation processes. This is naturally reflected in the heavy residues and was remarked upon in the field.

3). The Cockatoo Sands are the only soils of this area whose parent rocks are known with certainty; they are derived more or less *in situ* from the disintegration of Devonian sandstones, and are readily distinguishable from the other soil types.

The characteristic features of the heavy residues of typical soil profiles are given in table 3.

Cununurra Clay. Perhaps the most noticeable feature of this soil is the variation in amount of heavy residue as shown by Table 3. The soil (in the silt fraction) is characterized by the relatively constant percentages of amphibole, epidote, garnet, hypersthene, and opaque minerals (ilmenite, limonite) throughout the profile, and the falling off in the percentages of tourmaline and zircon. Other mineralogical points are:—sporadic occurrence of rutile; apatite; andalusite; mica (in lower part only); and magnetite (see table 3). Varietal features of certain minerals are important in diagnosing the parentage and history of certain of them. Such features are found in zircon (rounded and angular); tourmaline (color and roundness); amphibole (several varieties, the most prominent of which is blue-green and strongly pleochroic).

TABLE 2

	Cununurra Clay H.R. %		Meruin Sandy Loam H.R. %		Cockatoo Sand H.R. %	
Grade	+90	−90	+90	−90	+90	−90
	1.0	2.1	2.8	12.3	.07	.4
	.8	2.8	3.0	15.5	.07	.26
	.8	3.0	3.1	13.5	.03	.22
	2.1	4.9	4.6	15.0	.05	.26
	3.2	11.6	7.2	11.6	.05	.24
			9.8	26.2	.03	.16

H.R. = heavy residue; +90 mesh, sand passing a 60 mesh sieve, approx. 0.25 mm. and retained on 90 mesh approx. 0.14 mm. in diameter of opening; −90 mesh, sand approx. 0.14 to 0.02 mm.

Each set of figures represents samples from one profile of the particular soil type.

Mantinea Clay. This soil is very similar mineralogically to the Cununurra Clay, the most noticeable feature being the increase in quantity of tourmaline and hypersthene. This heavy residue shows more admixture of mineral matter from sedimentary sources (92 per cent Pre-Cambrian, 8 per cent sediments) than the Cununurra Clay. The percentage of heavy residue, taken as a whole, is less than for the Cununurra Clay, that at 72 inches only corresponding to the surface layers of the former. Only a trace of magnetite is present.

Ord Sandy Loam. No complete soil profile has been examined mineralogically, but samples from 0–6 inches and from

84–90 inches can be considered representative. The percentage of heavy residue is quite high, 7 and 5 per cent respectively, with 1 and ¼ per cent magnetic fraction. The heavy mineral assemblage appears to be fairly uniform throughout and small quantities of a great variety of minerals such as apatite, andalusite, sphene, brown mica, anatase and rutile, occur. The clay beneath the Ord Sandy Loam contains the same variety of minerals, but the heavy residue is less (1.5 per cent), and the proportion of hypersthene and garnet to the other minerals appears to be greater.

Meruin Sandy Loam. The silt grade contains a high percentage of heavy residue which increases somewhat with depth (see table 3). The magnetite content is also unusually high when compared with other residues of soils from the area. Of the other heavy minerals ilmenite, amphibole, and epidote are fairly regular in distribution; garnet is plentiful in all but the surface layer; and zircon rather more abundant than in other residues, with the exception of the Cockatoo Sand. There is a good variety of "accessory" minerals which show varietal features of interest, i.e. glaucophane. Although there are some features of the residues which differ from those of the

TABLE 3

Soil	H.R.*	M.F.*	Characteristic features	Remarks
Cununurra Clay	Up to 3% for 24″, then ½% to 48″; to 11% in 53–75″	Small at surface, rising to 2.6% at 75″	Amphibole, epidote, garnet in angular grains	Marked variation in H.R., zircon, and tourmaline content with depth
Martinea Clay	½–1% at surface; 2% at 72″.	trace	Amphibole, epidote, garnet, tourmaline, zircon, rutile, hypersthene	Little variation in H.R. but no complete profile available
Ord Sandy Loam	7% at surface; 5%, 84–90″.	1% .23%	Amphibole, epidote, prominent; garnet; tourmaline hypersthene, zircon, andalusite as minor constituents	No complete profile
Meruin Sandy Loam	12.3% 15.5 13.5 15.0 11.6 26.2	5.3% 6.4 5.2 6.0 4.3 11.2	Similar to Cununurra Clay; amphibole, epidote, garnet, zircon, tourmaline *rutile*	Differs from Cununurra Clay in presence of rutile and increased H.R. and magnetite. Some variation in profile
Junction Complex	0.2% at surface and at depth	trace	Zircon, tourmaline, rutile, garnet, amphibole, epidote	No complete profile. H.R. is a mixture of that of Cununurra Clay and Cockatoo Sand
Cockatoo Sand	½% rising to 1% at depth	trace	Zircon, tourmaline (well rounded); little epidote; scarce amphibole; rutile, anatase	Uniform throughout profile

* Per cent in the −90 grade; H.R. = Heavy residue; M.F. = magnetic fraction.

Cununurra Clay it is considered that the fundamental mineral assemblage has been derived from very similar sources to those of the Cununurra Clay. The greatest difference is the increased percentage of magnetite, which indicates either a new source of material or conditions of deposition which have caused an accumulation of heavy minerals.

grains are all moderately to well rounded, and have the typical appearance of those of old sedimentary rocks whose materials have been subjected to much mechanical wear.

The sandstones associated with these soils were also examined, and the heavy residues were found to be practically identical with those of the soils. Table 4

TABLE 4

Sample No.		1	2	3	4	5
Retained on	Mesh opening mm.	%	%	%	%	%
32	.49	—	—	—	—	.6
60	.24	30	28.8	14.23	11.1	21.0
115	.12	61.2	56.3	51.3	55.0	58.5
250	.06	8.1	12.9	31.2	27.3	17.1
−250 (Tyler sieves)	—	.72	1.9	3.26	6.6	2.8

1. Sandstone, west side Kelly's Knob.
2. Sandstone, weathering, 30 ch. east of Kelly's Knob.
3. Sand from base of sandstone, same locality as 2.
4. Sandstone weathering *in situ*, Carlton Reach Hills.
5. Sandstone weathering *in situ*, Carlton Reach Hills.

Junction Complex. Only the residues from one profile, representing the surface and from 48 to 60 inches, were examined. The heavy mineral assemblages when analyzed critically were found to be nearly half way between that of the Cununurra Clay and the Cockatoo Sand (see table 7), which confirms the opinion formed in the field (Burvill). The most striking feature is the association of well rounded zircon and tourmaline with angular amphibole.

Cockatoo Sand. The heavy residues of this soil type are characterized by being only a very small percentage of the sand grade, and this percentage does not vary much throughout the profile. There is only a trace of magnetite. The mineral assemblage consists of ilmenite, zircon, and tourmaline, with minor amounts of such other minerals as anatase (authigenic), andalusite, rutile, a little epidote, and amphibole, staurolite, sphene, and corundum, the two latter being quite scarce and of sporadic occurrence. The

shows the mechanical composition of the Cockatoo Sand and the Devonian sandstone (known as the Cockatoo Sandstone) from which it has formed *in situ*.

The sandstones are cross-bedded and pinkish-brown in color, and the figures in Table 4 indicate that they are well-graded, and that the sand (No. 3) into which they distintegrate is very similar in grading. Variation in percentage of the +60 and of the −115 +250 grades is due to slight differences in the sandstone beds themselves.

Heavy residues were separated from the −115 +250 grade of each sandstone and were consistently small, generally less than one quarter of one per cent, of that grade.

SOURCE OF THE HEAVY RESIDUES

The heavy residues of typical soil profiles show a considerable variety of minerals, the proportions of which may vary markedly. This variation is set out in Table 5 which gives the estimated propor-

TABLE 5. *Heavy minerals present in typical soil profiles**

Soil	Cununurra Clay					Mantinea Clay			Ord Sandy Loam		Merlin Sandy Loam						Cockatoo Sand						Junction Complex	
Depth (inches)	0–6	6–24	24–45	45–52	52–75	18–20	54	72	0–6	84–90	0–5	5–27	27–48	48–60	60–69	69–84	0–9	9–30	30–60	60–87	87–108	108–144	0–1	48–60
Heavy Residue	% 2.1	% 2.8	% 3.0	% 4.9	% 11.6	% .43	% .54	% 1.2	% 7.3	% 5.5	% 12.3	% 15.5	% 13.5	% 15.0	% 11.6	% 26.2	% .4	% .3	% .2	% .2	% .2	% .1	% .1	% .1
Magnetic Fraction	.3	tr.	tr.	1.6	2.6	tr.	tr.	tr.	1.0	.23	5.3	6.4	5.3	6.0	4.3	11.2	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.
Minerals																								
Opaques	7	8–	7	7–	7–	7	7+	7	6	6	7+	8–	8–	7+	7–	7–	6+	6+	6+	6+	7–	6+	8	8–
Amphiboles	7–	6+	7–	7+	7+	7+	7	7+	8–	8–	6	6+	6	7	7–	7–		1	1		1	1	4	2
Anatase	1						1†	1		1	1†				1†		1	2	2	2	3	2		
Andalusite	1	1							1										1		1	1		1
Apatite					1		1		1	1														
Chlorite			1	2					1														1	
Epidote	6	5	6	6	6	5	5	5	5	5	5	5	5	4	6	4	2	1	1				2	1
Garnet	4	4	4	4	4		2	4	1	1		3	4	4	4	3							3	1
Glaucophane																1								
Hypersthene	1	1	1	1	1	2		2	1	1	1					1								
Iddingsite (?)								1							1	1								
Mica (biotite)								1	3															
Monazite			1	1†																				
Pyroxene	1																							
Rutile	1		1	1		1	1	1		1	1	1†	1		2	2	3	2	2	2	3	2		1†
Serpentine																								
Sillimanite																								
Sphene		1†	1							1														
Staurolite			1†													1								
Tourmaline	4	3	2	1		3	4	3	1	1	2	3	1	1	1	1	7–	7	7–	7	7–	6+	5	6
Zircon	5	5	4	2	2	4	3	4	1	1	2	3	4	3	3	4	6+	7	7–	7+	7–	7+	3	
Zoisite	2	2		2							1	1												

* These heavy residues are from fine sands whose grains are between 0.14 and 0.02 mm. in diameter.
The numbers signify various estimated amounts of each mineral in the heavy residues according to the following scheme:

8, abundant.
7, fair amount.
6, common.
5, small amount.
4, rather scarce.
3, scarce.
2, infrequent.
1, rare.
1†, one grain only observed.

tions of each mineral. The figures are modifications of the method advocated by Evans, Hayman and Majeed.

The latest geological map (Matheson and Teichert) shows that the Ord River from about Lat. 18°S. flows across a terrain of Cambrian limestones, shales, basalt; Permian (?) sandstones and shales; Pre-Cambrian phyllites and quartzites; and Devonian sandstones. Immediately above the proposed irrigation area, the soils from which are described here, the Ord cuts through more than fifty miles of Pre-Cambrian country.

The heavy mineral assemblage of the principal type of soil (the Cununurra Clay) shows that minerals derived from metamorphosed rocks are more promi-

TABLE 6

Mineral	Varietal Features of *Significance*	Remarks	Parent Rock (Probable)
Amphibole (several types)	Fresh angular appearance, bright bluish green; $Z \wedge c = 24–26°$. Pleochroic	Metamorphic type	Hornblende schist, phyllite
	Pale green, $Z \wedge c$ very small	*Metamorphic type*	*Phyllite, greenstone*
	Brownish green, $Z \wedge c = 20°$	Has been recorded in basalt	(?) Basalt
Anatase	Flat, tabular, steel-blue or pale yellow	Authigenically formed in sandstone	Sandstone
Andalusite	Angular and sub-angular, some grains worn	Metamorphic type	Schists
Apatite	Generally not rounded	—	*Schists; no granites in* in eroded area
Chlorite	Pale green	Alteration product	Phyllites
Chlorite	*Yellow-green, pleochroic*	*Recorded in basalts*	(?) Basalt
Corundum	—	Very scarce	Meta-sediments
Epidote	Bright color, fresh appearance	Also present in some sandstones	Greenstones, schists
Zoisite			
Garnet	Angular, pink to brown in color	Colorless garnet present in sandstones	Schists, greenstones
Glaucophane	Typical appearance	Occurs only in one soil type	Schists
Hypersthene	*Schiller structure, worn* appearance	Also in some sandstones	Gabbro and other basic rocks
Iddingsite (?)	—	—	Basalt
Ilmenite	—	—	Many sources
Limonite	—	—	Many sources
Magnetite	—	—	*Many sources*
Mica (biotite)	Bright brown color, fresh appearance	—	Phyllites, shale
Monazite	—	Sporadic occurrence	
Pyroxene	Worn appearance; pigeonite type in one residue	—	Basalt, greenstone
Rutile	Worn appearance, brown	—	Probably mostly from sedimentary rocks
Serpentine	—	Possibly altered olivine	*Basalt*
Sillimanite	—	Scarce, sporadic	Schists, gneisses
Sphene (*titanite*)	—	—	Greenstones
Staurolite	—	Scarce, sporadic	Schists
Tourmaline	Angular and well-rounded, many colors	Spherical grains in some sandstones	Pegmatites, schists
Zircon	Several habits; colorless and brownish purple; angular to rounded	Derived from two or more sources, one of which is sedimentary	Schists, gneisses, possibly greenstones
Zoisite	See epidote		

nent than those from other sources. This is to be expected because such minerals are much more resistant to chemical and mechanical disintegration than those which occur in such rocks as basalt, for example. The contribution of heavy detrital minerals from most sedimentary rocks is small and is apt to be confined to a few species, which will therefore be overshadowed by the greater variety and freshness of minerals from a newly eroded igneous and metamorphic terrain, whether this be Pre-Cambrian, as in the Kimberleys, or of younger age. Basaltic rocks weather fairly readily and are probably able to contribute more soil per cubic foot of rock in a given time than would be obtainable from schists, gneisses, phyllites, etc., under similar conditions.

Although the Cununurra Clay is underlain at depth by basalt and limestone, the heavy mineral assemblages of the soils to a depth of 13 feet (where sampled) could not have been derived from basalt containing as they do such species as blue-green amphibole, garnet, andalusite, and tourmaline. The clay, making up the bulk of this soil, represents redeposited soils, and it is possible that basalt contributed largely to it, although very few detrital minerals can be specifically assigned to such basalts which are fine-grained and contain very few resistant minerals.

The main points of interest and the varietal features of the heavy minerals are set out briefly in Table 6.

From a consideration of the varietal features of the minerals and their associations, together with some knowledge of the rocks of the distributive province the following main sources of material are suggested:—

One of the most noticeable features of these residues is the association of strongly colored angular amphibole with well rounded tourmaline and zircon. Accompanying the amphibole there is nearly always epidote and zoisite, together with angular garnet some of which is strongly colored in pink or brown.

There is, however, a marked difference in the proportion of these minerals. Leaving out of consideration the rather indefinite mineral assemblage supposedly contributed by basalt, an interesting relationship can be shown by assessing

TABLE 7

Pre-Cambrian	Sedimentary Rocks	Basalt
Amphiboles	Anatase	Chlorite
Andalusite (in part)	Andalusite	(?) Iddingsite
Epidote, zoisite	Garnet (in part)	Ilmenite (in part)
Mica	Hypersthene (in part)	Magnetite (in part)
Garnet	Ilmenite (in part)	Hornblende (brown)
Ilmenite (in part)	Rutile	Pyroxene
Hypersthene	Staurolite	Serpentine
Magnetite (in part)	Tourmaline	
Apatite	Zircon	
Tourmaline (in part)		
Zircon (in part)		

TABLE 8

Soil Type	Source	
	Pre-Cambrian Rocks %	Younger Sedimentary Rocks %
Cununurra Clay	97	3
Mantinea Clay	92	8
Ord Sandy Loam	98	2
Meruin Sandy Loam	97	3
Junction Complex	43	57
Cockatoo Sand	—	100

Note: the opaque minerals and magnetite have been omitted, the remainder being calculated to 100%.

the contributions (from the tabulated results of which Table 5 is a part) that the Pre-Cambrian and younger sedimentary rocks have made to the soil residues.

CONCLUSIONS

The gray plains soil, Cununurra Clay, of the lower Ord River valley is probably comparable with the soils of the Barkly Tableland in the Northern Territory which Whitehouse has recently described. He suggested that such soils are for the most part Pleistocene deposits, "transported soils of the old alluvium, particularly the later phases of it." The transportation was due to a period of higher rainfall during part of the Pleistocene period.

An examination of the detrital minerals of the Ord River valley soils clearly shows that they are of mixed parentage such as would result from the deposition of alluvial material from several sources. Soil forming processes which have taken place since deposition of the alluvium apparently have not destroyed the evidence of such deposition as a layering or bedding is still recognizable. A critical examination of the heavy mineral assemblages affords a means of distinguishing soil types and strengthens field evidence of their origin.

ACKNOWLEDGEMENT

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FIGS. 1–2, APRIL, 1947

RHOMBOID RIPPLE MARKS AND THEIR RELATIONSHIP TO BEACH SLOPE[1]

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ABSTRACT

Measurements of the acute angles of rhomboid ripple marks and their relationship to beach slope are tabulated and discussed. The motions of the backwash and the subsequent run-off are described with special reference to the mode of origin of rhomboid ripple marks.

Among the interesting minor features of modern beaches are the "backwash marks" noted by Johnson, later termed "rhomboid ripples" by Bucher. Describing the results of experiments by H. Engles (1905) at Dresden, Bucher states,

"... the first effect of transportation by a uniform current was the formation of small rhomboidal, scale-like tongues of sand, arranged in a reticular pattern, strikingly resembling that of the scales of a Ganoid. Each tongue has one acute angle pointing down stream, formed by two steep leesides, while the other, pointing up stream, formed by the gentle slope extending into the reentrant angle of the leesides of two tongues of the following, alternating row."

During August, 1944, and July, 1945, an examination was made of rhomboid ripple marks occurring along one mile of

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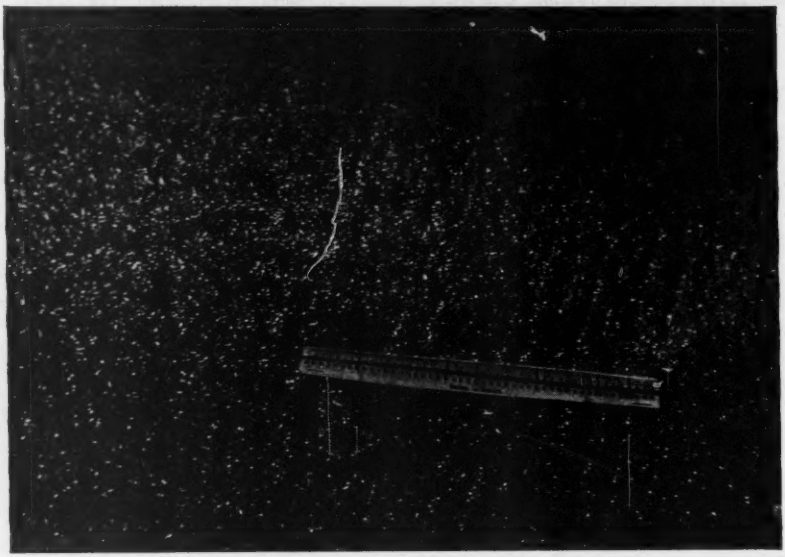

FIG. 1.—Rhomboid ripple marks, Sea Girt, N. J.

beach at Sea Girt, New Jersey (fig. 1). A large number of measurements of rhomb angles, beach slope, and backwash velocities were made in an attempt to determine the relationship of rhomb angles to beach slope, and to study possible modes of origin of rhomboid ripple marks.

The beach at Sea Girt is composed mainly of very coarse quartz sand. Pebbles and shell fragments are abundant, especially in a zone at the foot of the beach slope, where they are continually moved about by the breaking surf. The shoreline is straight and trends N. 30° E. The average prevailing onshore wind direction for several sucessive days in July, 1945, when all the measurements used in this paper were made, was S. 45° E with but little variation. Consequently, the waves regularly

1. *Normal Beach—Single measurement per backwash*

Feet from Pebble Zone	Angle of Beach Slope	Rhomb Angles (Degrees)	Average
0′	9° (est.)		
6′	9°	Rill marks, no distinguishable rhombs	
12′	10° 20′	32, 35, 33, 36, 35, 34, 35, 34, 36, 35, 33, 33, 37, 36, 36	34° 40′
18′	12°	37, 38, 40, 40, 37, 41, 41, 39, 38, 39, 42, 38, 39, 38, 37	38° 56′
24′	12° 30′	None	

2. *Normal Beach—Paired measurements following the same backwash*

Feet from Pebble Zone	Angle of Beach Slope	1	2	3	Average
0′	9° (est.)	—	—	—	—
6′	9°	Rill Marks	Rill Marks	Rill Marks	
12′	10° 20′	35	33	34	34°
18′	12°	39	38	39	38° 40′
24′	13° 30′	None	None	None	None

3. *Nose of Cusp—Paired measurements following the same backwash*

Feet from Pebble Zone	Angle of Beach Slope	1	2	3	Average
0′	9° (est.)	—	—	—	—
9′	10°	38	35	35	36°
15′	11°	40	40	38	39° 20′
21′	12°	None	None	None	None

4. *Inter-Cusp Area—Paired measurements following the same backwash*

Feet from Pebble Zone	Angle of Beach Slope	1	2	3	Average
0′	9° (est.)	—	—	—	—
6′	9°	Rill Marks	Rill Marks	Rill Marks	
12′	9°	Rill Marks	Rill Marks	Rill Marks	
18′	9°	34	32	35	33° 40′
24′	7°	40	39	38	39°
30′	7°	None	None	None	None

approached the beach at an angle of 15° or slightly less, and were uniformly about 2 to 2.5 feet in height. In order to eliminate extraneous factors in so far as possible, observations were recorded only during periods of about an hour and a half following the turn of high tide.

The rhomb angle measurements presented here are of three types. The first and most numerous are those that were made on a normal, straight beach without cusps, the crest of which was between 4 and 4.5 feet in elevation higher than the lowest point of the beach exposed by the retreating backwash. This point corresponds to the pebble zone mentioned above. The other types of measurement were made at a time when recently formed beach cusps had just begun to undergo destruction. Observations were made at the center of the inter-cusp area as well as on the noses of the beach cusps. The cusps were about 30 feet apart, and the beach crest of the inter-cusp area was about 4 or 4.5 feet above the pebble zone. The highest point on the nose of the beach cusp was a few inches lower than the crest of the inter-cusp area. Rhomb angle measurements for all three types were made following the backwash of waves that reached within a foot or two of the crest of the beach. A summary of rhomb angles to the nearest degree is presented below in tabular form, including the corresponding angle of beach slope and the approximate position of the rhomb angle, measured in feet from the pebble zone at the foot of the beach.

The measurements show beyond doubt, as Woodford predicted, that the "more acute rhombs are to be found down the slope." The water, as it flows down the beach appears to accelerate enough to cause the rhomb angles to become more acute, but the range of error in measurement is too great, as shown in the above tables, for any precise comparison of rhomb angles formed under slightly different rates of acceleration occurring on beach slopes of varying steepness. The extreme limits of beach slope conducive to rhomb formation were found to be 6 to 12 degrees. Rhombs were rarely found on 6 degree slopes, and on slopes of 13 degrees or more the sand appeared to be too mobile to preserve the rhombs, if any were formed.

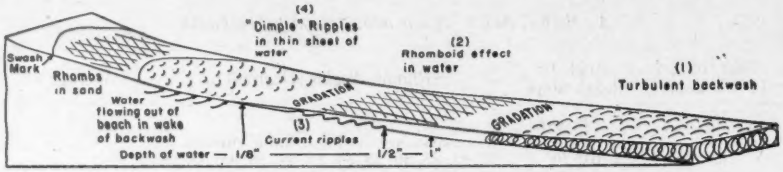

DIAGRAM SHOWING BACKWASH STAGES

FIG. 2

Any explanation of the origin of rhomboid ripple marks must first take into account the motions of the backwash that preceded their formation. A typical backwash, produced by waves such as those described above, flowing down a straight cuspless beach can be divided into a number of gradational but recognizable stages (fig. 2). Under the most favorable conditions all these stages may be present at one time in several parts of a single backwash, but they can be more easily studied by observing the changing form of the receding backwash water as it passes a point about mid-way between the swash mark and the pebble zone. Viewed in this way, the following stages can be noted in succession:

1. During the first stage the backwash is composed of turbulent water rushing down the beach slope, carrying with it many sand grains, pebbles, shell fragments and air bubbles. The internal mo-

tion of the water appears to be completely random. The depth of water in this stage may diminish from 24 inches or more at the start to slightly less than one inch. The average velocity of the turbulent stage, measured 15 times over a 20 foot course was a little under 6 seconds (plus or minus one second), or an average velocity of nearly 4 feet per second.

2. When the depth of water falls below one inch, a rhomboidal pattern quickly forms on the surface of the water. This has the appearance of a rough, criss-cross woven pattern, visible only for a few moments. A similar effect may occur when two slightly conflicting tongues of backwash meet and merge.

3. At a depth of less than one-half inch, while the rhomboidal effect is still present on the surface of the water, small current ripples of an inch and one half wave length begin to develop in the sand, and migrate rapidly down the beach slope.

4. In the closing stage of the backwash the rhomboidal effect on the surface of the water completely disappears, and almost immediately thereafter the current ripples in the sand become indistinct and merge into the mobile mass of sand flowing slowly down the slope.

These four main stages comprise the true backwash. However, closely following stage four, a thin sheet of water less than one-eighth inch thick quickly spreads over the beach slope from top to bottom. This water is derived from the saturated beach sand, into which large quantities of water seep when the swash is at its greatest extent. When the retreating backwash uncovers the beach, the water seeps back to the surface a little farther down the slope, the result approximating a rapidly advancing line of miniature springs following the backwash down the beach slope. The velocity of this water is only about half that of the turbulent backwash. Fifteen measurements on a 10 foot course gave an average of 5 seconds (plus or minus one second), or an average velocity of 2 feet per second.

Innumerable small ripples form on the surface of this thin sheet of water, giving a dimpled appearance to the otherwise smooth, almost glassy surface. These ripples seldom become more than six inches across. They appear semi-circular, and are propagated down the slope only, with the convex side pointing downward. In their course down the beach they overlap, merge and disappear in a distance of about 10 feet. Probably these "dimple" ripples are caused by small masses of water emerging suddenly on the beach surface, and thus forming minor centers of disturbance at varying intervals, according to the local porosity, permeability, and saturation of the beach sand.

Rhomboid ripple marks in the sand are not formed until an instant before the end of the thin sheet of water passes. The beach slope at this time is corrugated by very low flat ridges normal to the trend of the beach and about 2 feet apart, with intervening shallow valleys. This slight corrugation is caused by the tendency of the backwash to form parallel streams, which erode a small fraction of an inch of sand where they flow. The rhomboid ripple marks appear first on the ridge areas, then spread to the valley areas, and are immediately etched into the beach by the last remnants of the thin sheet of water.

The rhomb angles appear to be caused by the conflict between the flow of water directly down the beach slope and the radial effect of the ripple impulse. For a fuller description of this interference effect see Woodford's paper, quoted above. In still water a ripple impulse will extend equally in all directions as a perfect circle, but in flowing water the extension of the ripple is modified by the direction and velocity of the current. When the velocity of the current is greater than the velocity of the ripple impulse, the extension of the ripple can be only downstream or obliquely downstream. The maximum angle of obliqueness is the resultant of the velocity and direction of the main current plotted against the velocity of the ripple impulse at right angles to the main current. When the depth of water diminishes nearly to zero the strength of the ripple

impulse becomes greater than the strength of the main current of water. At this instant the maximum angle of obliqueness determines the direction of flow of enough of the remaining water to cause an approximation of that angle to be eroded into the sand. The simultaneous formation of many of these angles in juxtaposition causes the rhomboid pattern.

CONCLUSIONS

The first prerequisite to the formation of the rhomboid ripple marks is the thin sheet of water that flows down the beach slope in the wake of the true backwash. This sheet can occur only when the upper part of the saturated beach is yielding its water of saturation copiously, owing to the hydraulic gradient in the sloping beach and permeability of the sand. Of course, the porosity of the beach sand must be high enough to contain sufficient water, and the permeability must be adequate to release the water quickly as the backwash recedes.

Secondly, the beach must have the proper range of slope. At Sea Girt a range of 6° to 12° permitted sufficient acceleration to form rhomboid ripple marks, but not enough to destroy them in the sand flow that would occur on a steeper slope.

Finally, the "dimple" ripples appear to be the minor disturbances needed to deflect small quantities of water from a straight course in the final run-off down the beach slope. The rhomb angles agree with the maximum angles of current deflection that would be expected when such disturbances can be extended only downstream or obliquely downstream in flowing water that is traveling faster than the ripple impulse.

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PLATES 1–2, APRIL, 1947

EXPERIMENTS ON THE DEVELOPMENT OF TRACKS IN FINE CROSS-BEDDED SAND

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ABSTRACT

Evidence bearing on the type of environment represented by the track-bearing, cross-laminated Coconino sandstone of Permian age in northern Arizona has been obtained through a series of experiments. Using both reptiles and invertebrates an attempt has been made to develop in fine-grained sand, tracks that are comparable to those in the sandstone, thus demonstrating the conditions required for their development. Track variations due to differences in degree of sand slope, in moisture content of sand, and in direction of the animal's movement were observed and noted.

The conditions required for the development and preservation of tracks and trails in sloping layers of fine sand have been a matter of considerable speculation. Interest in the subject was first aroused in 1918 through the discovery of fossil footprints on cross-lamination slopes of the Permian Coconino sandstone in northern Arizona. Here five toed tracks left by vertebrate animals (pl. 2, figs. 5, 6) of various sizes and proportions are found in abundance on otherwise smooth bedding surfaces that have an initial dip ranging, in most cases, between 25 and 30 degrees. Trails left by invertebrates are also represented, but these are confined to beds dipping at low angles (less than 12 degrees).

Several features of unusual interest relative to the Coconino tracks are readily apparent and must be taken into account in any satisfactory explanation of origin. First, the prints are almost invariably sharp and clear, without showing wavy or irregular margins. Second, in nearly every case the vertebrate footprints lead uphill, only three exceptions being known where the toes point down the slope of the bed. Third, the tracks are preserved in fine-grained ($\frac{1}{8}$–$\frac{1}{4}$ mm.), clean, white quartz sand of uniform character. A review of various investigations made of these tracks and of attempts to explain them has previously been presented by the writer (McKee, 1944), together with an account of some experiments relating to their origin. A summary of the experimental work on development of tracks in fine sand is the subject of this paper.

In an attempt to duplicate in the laboratory various features of the tracks found in the Coconino sandstone, three variable factors that controlled results were taken into consideration. These were the degree of slope of the sand surfaces, the moisture content of the sand, and the size of the animal. Furthermore, sands of several types were tried, but because all gave similar results, the sand most nearly resembling that of the Coconino in size and degree of sorting was employed. This was a dune sand having well-rounded grains averaging between $\frac{1}{16}$ and $\frac{1}{8}$ mm. in diameter and displaying excellent sorting, obtained from the Navajo Indian Reservation at Tuba City.

All experiments on the development of tracks in fine sand were made in the laboratory of the Museum of Northern Arizona at Flagstaff. The writer was ably assisted in this work by Messrs. L. F. Brady and Joseph Snow and Miss Betty Lou Decker. The apparatus used consisted of a narrow sixteen-foot wooden trough with one end darkened by a cover and the other exposed to full sunlight. In the central portion, sand was piled up into a ridge, sloping off on each side at

PLATE 1

FIG. 1.—Tracks of milleped in Coconino sandstone.
FIG. 2.—Tracks of reptile in wet sand, uphill, 33 degree slope.
FIG. 3.—Tracks of milleped in dry sand, 18 degree slope.
FIG. 4.—Tracks of reptile in wet sand, uphill, 28 degree slope.
FIG. 5.—Tracks of reptile in damp sand, uphill, 28 degree slope.
FIG. 6.—Tracks of reptile in damp sand, downhill, 28 degree slope.

any desired angle. Animals used in the experiments were placed in the dark end of the trough and, being attracted by light at the opposite end, would travel in that direction, walking up one side of the sand hill and down the other. Thus, one set of tracks leading uphill and another going downhill were obtained from each trip made by the animal. When desirable, tracks on the sand surfaces were permanently preserved by spraying with a solution of alvar until a rigid crust was formed and the entire layer of sand could be removed.

It is not known whether the vertebrates that made tracks in the Coconino were reptiles or amphibians or both (McKee, 1944, p. 62), but they varied greatly in size and represent a wide variety of forms, few of which dragged their tails. They walked on all four legs and many of them left definite pointed toe or claw impressions. In the experiments, several types of lizard, including varieties of *Sceloporus* and *Uta* and a large chuckwalla (*Sauramalus ater*), were employed. These reptiles apparently had the general proportions and type of locomotion represented in the ancient tracks. The chuckwalla gave the most satisfactory results for it had sufficient weight to make footprints in wet and damp sand as well as in dry. Furthermore, its tracks were approximately the size of those referred to *Laoporus nobeli* (pl. 2, fig. 5), commonest species in the Coconino, suggesting that the chuckwalla was comparable in size and weight to that animal and might be expected to sink into the sand about the same amount under similar environmental conditions. Large millepeds of the order Spirostripidae were also used in the experiments for their trails are closely similar to some found in the Coconino sandstone. Other invertebrates, resembling modern scorpions and wood lice, probably also are represented by their tracks in the Coconino. These were tested in earlier experiments by Brady (1939).

In order to determine the degree of moisture in sand required to retain track impressions comparable to those of the Coconino sandstone, tests were made using (1) thoroughly wet sand, (2) damp sand, i.e. sprayed with a light mist of water that did not penetrate to depth, (3) loose dry sand, (4) sand that had been thoroughly wet and then allowed to dry, and (5) sand that had been damp and allowed to dry. It was found that the lighter animals, such as the small lizards (*Uta* and *Sceloporus*) which weigh between 4 and 5 grams and the invertebrates, including millepeds, failed to break through the surface of any but loose dry sand. As a result they left only small toe scratches or no marks at all on sand which was or had been either wet or damp.

Experimenting with the chuckwalla, which was about four times as long as the other lizards (14 inches) and weighed considerably more (132.5 grams), very different results were obtained. Because of greater weight, it formed definite toe marks but nothing else while going uphill in wet sand (pl. 1, figs. 2, 4). Downhill in the same medium, it left only the suggestion of footprints. In damp sand, both uphill and downhill, it would repeatedly break through the thin crust (about 1 mm.) formed on the surface, thus leaving a jumbled mass of broken patches and curls in its path (pl. 1, figs. 5, 6). The same results were obtained even when wet or damp sand was subsequently dried out completely. Only in loose dry sand did the chuckwalla form clear, well-defined footprints (pl. 2, figs. 1, 2, 3) comparable to those preserved in the Coconino sandstone.

Varying the slope of the sand surface on which the animals walked resulted in further differences in the tracks. Records were made (1) on a 12° slope which is approximately the maximum on the windward side of dunes, (2) on a 28° slope which is common on the lee sides of dunes, and (3) at 33° which is the angle of repose for the sand used. On the low-angle slope all lizard tracks, both uphill and downhill, were sharply defined in dry sand. At the angle of repose, however, downhill tracks were completely de-

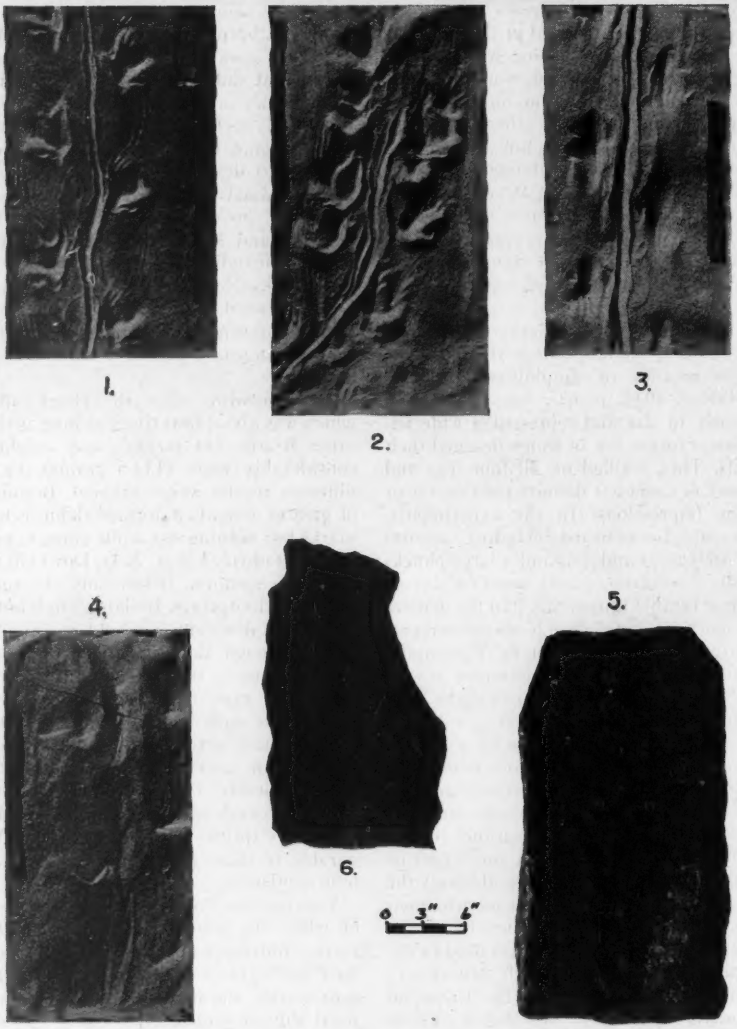

PLATE 2

FIG. 1.—Tracks of reptile in dry sand, uphill, 20 degree slope.
FIG. 2.—Tracks of reptile in dry sand, uphill, 28 degree slope.
FIG. 3.—Tracks of reptile in dry sand, downhill, 20 degree slope.
FIG. 4.—Tracks of reptile in dry sand, uphill, 28 degree slope (lizard running; all others made with lizard walking).
FIG. 5.—Tracks of *Laoporus nobeli* in Coconino sandstone.
FIG. 6.—Tracks of *Laoporus schucherti* in Coconino sandstone.

stroyed and most uphill tracks partially destroyed by sliding and slumping of the sand surface. This was the result of disturbance to the delicate balance of the sand slope, especially when the reptile, coming downhill, attempted to check involuntary sliding by using his feet for brakes. At a somewhat lower angle (28°) uphill tracks were for the most part well-developed, but downhill tracks were destroyed by slumping as on slopes of thirty-three degrees.

Millepeds were unsuccessful in climbing loose sand hills where the slope was in excess of twenty degrees. On steep slopes they would invariably slide backward or lose balance and roll downhill, but at lower angles they left clear tracks both up and down the slopes (pl. 1, fig. 3). Trails formed during the ascent appeared as double grooves in the sand surface, whereas those formed while coming down had three grooves as a result of spreading the legs and dragging the body to avoid sliding. Both types have been recognized on surfaces of Coconino sandstone (pl. 1, fig. 1).

Variation in track character resulting from degree of sand slope is significant when considered with respect to the Coconino sandstone. In this formation nearly all of the surfaces of cross-lamination dip at angles of 25° or more, being the result of deposition on the lee sides of sand dunes. On such steep slopes only the *uphill* tracks of quadrupeds are found and, as might be expected, there are no invertebrate trails. In contrast, rare low-angle deposits, formed either on windward slopes or at the basal margins of lee slopes, contain the trails of millepeds and scorpions as well as both uphill and downhill tracks of vertebrates.

No experiments were made by the author to determine the type of tracks formed in fine sand under a standing body of water, but work by Peabody (1946) on amphibians has shown that clear tracks are very difficult, if not impossible, to obtain under such conditions. His results are summarized in the following statement:

"In the process of obtaining trackways from a total of 45 species, representing 20 genera of living salamanders, I had to consider the possibility of a clear underwater record of the alternating walk of quadrupedal vertebrates. Experimentation with different recording media such as mud, sand, and smoked paper under different conditions has convinced me that it is practically impossible for a salamander to record a diagnostic trackway under water. The greater buoyancy of the salamander in water precludes a weight distribution similar to that which is present during locomotion on land. Under water the salamander finds it easier and more convenient to swim from place to place. When leaving the water, it swims to shore and then walks out on the land. In water which is too shallow to cover it, the salamander wriggles along with a combination of swimming and walking movements which produce a trackway open to only the broadest interpretation.

"Many observations on recent mudflats and the collection of numerous subaerial trackways therefrom have failed to discover a single instance in which the local amphibians, reptiles, or mammals left any underwater trackways. Consecutive kick marks of a swimming frog or wading trackways of birds such as the bittern may be found, but no occurrence of a diagnostic trackway recorded by a vertebrate completely immersed in water has been noted. Such "wading" trackways as I have observed show the trackway pattern well enough but details of the individual footprints are poorly shown."

The experiments described above suggest that clearly-defined tracks in fine sand, such as those represented in the Coconino sandstone, are best explained as having been formed when the sand was dry. Studies of aeolian ripple marks and of dune slump marks (McKee, 1945, p. 324) which have been recognized in the Coconino indicate that they also were formed in a dry sand environment. This medium for development of the structure

could scarcely have been the one responsible for permanent preservation, however, for parting planes could not be formed merely by the addition of more dry sand. It has been suggested (McKee, 1945, p. 324) as a probable explanation of this feature that the sand layers containing tracks, ripple marks, or other structures may have been dampened as by a dew or fog to give a firm crust that remained even after the surface became dry, and that formed a parting plane when covered with loose, dry sand. Such dews are known to occur commonly in modern dune areas and were reproduced experimentally with a spray gun during the course of the footprint experiments, thus indicating the plausibility of this explanation.

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SEDIMENTARY PETROGRAPHY AND THE OIL INDUSTRY

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ABSTRACT

Applications of sedimentary petrography to the Oil Industry are reviewed critically; the methods of approach and techniques of investigation at present in use lead to an unbalanced appraisal of the petrology and petrography of sediments; suggestions are put forward for improvement by organized research and emphasis laid on petrography until sufficient observational data accumulate to lead to a fundamental philosophic background for the petrology of sediments.

I. INTRODUCTION

The applications of sedimentary petrography in the field of petroleum geology has essentially been restricted to the use of "heavy minerals" in problems of correlation, principally where other methods have failed. Grain size distributions (generally screen analyses) have also been very cursorily applied to reservoir problems without, in general, much attempt to understand the significance of either methods or results. The recent drive to locate new oil pools in the form of stratigraphic or petrographic traps has re-invigorated this field of investigation on a broader front and under the more general title of sedimentology. The lead may be considered to have commenced with the A.A.P.G. Symposium on Sedimentation (21). In that publication a number of views on the possible applications of sedimentary petrography *sensu lato* were expressed suggesting that investigations within this field could offer great assistance in exploration for new oil pools. As in many other similar cases, there was enthusiastic theorizing and some few tantalizing excerpts offered as exemplifying the type of reward to be expected. The actual results either of earlier work on correlation or subsequently the use of the method advocated in location of traps have not apparently been published. It is the purpose of this article to review the field presented and the reasons for the lack of advances to date, for it must be stated at the outset that little advance in the application of sedimentary petrography to the oil industry has been made to date.

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III. REVIEW OF POSSIBLE APPLICATIONS AND RESULTS

Sedimentary petrography, as its name indicates, deals with the petrography of sediments and includes studies of rocks in hand specimen, thin slice, grain size distribution, accessory minerals, the chemistry and physics of both minerals and rocks, clay petrography, classification of sediments, genesis, diagenesis, sedimentation, and palaeogeography. Each branch of study has something to offer in the way of information of value to the petroleum geologist; nevertheless the only branches studied have been the accessory minerals and some grain size distributions. The stage of development of each branch may be summarized briefly as follows:

1. *Description of Hand Specimen*

The macroscopic description (lithology) of sedimentary rocks has become routine practice and is an essential in

both field mapping and well correlation; indeed this "technique" forms the basis of most geological investigation. Unfortunately its familiarity has led to neglect of detail and, although recent trends (5) suggest improvements, it is extremely difficult to impress upon the average geologist the need for more than routine macroscopic description. There is no doubt that much more information of value to petroleum geology could be obtained by greater attention to this operation.

2. *Thin Slice Analysis*

The microscopic investigation of sediments in thin section is very rarely attempted. In general, one or two slices are cursorily described and emphasis is placed on the accessory minerals. In those few cases where thin slice technique has been carried out in some detail (11, 12, 34) the results have more than justified the operation; some of the reasons for the lack of detailed investigation are mentioned later.

Problems concerned with texture, orientation, cementation, and the study of the bulk minerals, quartz, feldspar, micas, etc. represent fundamental contributions to the study of aggregate properties of reservoir sands, while in the study of limestones this technique represents one of the main methods of approach.

3. *Grain Size Distribution*

The size distribution of sedimentary rocks has frequently been treated at length (10) and grain size distribution is often quoted in literature on oil sands particularly as a step in core analysis. In nearly every case (cf. 7, 11) a single analysis is given as typical of the reservoir sand; this is very rarely representative of such a variable entity as an arenite and while sufficient for the particular rock sample analyzed is not a satisfactory basis for defining gravel pack grain size or screen or slot sizes for the formation as a whole.

Another even more fundamental criticism is the tendency for most analysts to wash the sand free from clay and silt before commencing the analysis. This gives an entirely misleading idea of the grain size distribution of the sand and in the case of some sands known to the author (Trinidad and Venezuela) would result in discarding 50 per cent or more of the sample.

Considering the simplicity of routine grain size analysis of sediments (9) it is a cause for regret that most reservoir sands are not given an exhaustive investigation. The results could, of course, be of direct value in defining the uniformity of the reservoir, the classifying of the sand by comparison with other oil sands and with sediments of known origin (10), supplying basic information for gravel pack and screen sizes and indicating lensing out of sand. It should form the background for study of aggregate properties of rocks (core analysis) and in cases where discrepancies exist between size distribution and porosity, permeability, and saturation values, the interpretation of such discrepancies can give valuable information on reservoir characteristics.

4. *Accessory Minerals*

Studies of the accessory "heavy" minerals of sediments have been exhaustive and the sedimentary petrographer in the oil industry is generally known as the "heavy mineral man", an assumption which it must be admitted is usually correct. The use of heavy minerals in correlation has been stressed again and again; yet if a close scrutiny of the literature is made the number of successes is not very great. The results are summarized by stating that the "minerals transgress the time planes" or, to put it another way, are of facies rather than time significance. This is a very reasonable conclusion and one in full accord with theoretical principles. In general, it sets limits to the use of heavy minerals for correlation and in practice it is found that mineral assemblage distribution is useful for reconnaissance geology but that for detailed zoning of a limited vertical sequence, differences in mineral proportions are decided by very local changes in the area of deposition (22, 23, 25). Appli-

cations of the latest findings (22) are few as the method is too tedious and involved at present for use on the large numbers of samples generally handled in petroleum laboratories.

Another factor in the study of accessory (heavy) minerals has been the definition of provenance by allocating the heavy mineral assemblage to its source. Unfortunately it has only recently become obvious that such a practice is not straightforward and needs detailed studies to be of any real significance (3, 18, 21, 22, 23, 25, 26). All the results of accessory mineral investigations should be reviewed in the light of those recent and revolutionary publications.

Correlation by insoluble residues in limestones has become a routine (16, 24) where faunal studies have been unsuccessful.

5. *Chemical and Physical Properties of Sediments*

Very little detailed chemical investigations of sedimentary rocks have been undertaken and no attempt has been made, except in the case of clays and limestones, to interpret the bulk analysis of sediments in terms of the mineralogy. This again devolves essentially onto the lack of thin slice investigation. The trend has been indicated by Taliaferro (27) and Pettijohn (19); chemical analysis of sedimentary rocks could follow the procedure adopted by students of the chemistry of igneous rocks (8).

The mineral chemistry of reservoir rocks has been indicated by Krynine (11, 12) and such studies would, if sufficiently detailed, be extremely useful in predicting fluid behavior during injection for secondary recovery projects.

The physical (aggregate) properties of sedimentary rocks have been studied in some detail but unfortunately not by sedimentary petrographers and again the relationship between aggregate properties and mineral composition has not been attempted except in very few examples (7, 11, 12, 34). As a result, the measures (porosity, saturation, permeability) adopted for the average reservoir rock bear no relation to the rock itself and frequently no relation to fluid behavior under field conditions. These values can never be accurately interpreted without due acknowledgement to mineral composition, shape, and arrangement (6).

6. *Clay Petrography*

No attention has been paid to the role of clay petrography in the oil industry, despite its obvious significance, (6) and although the uses of clay in the oil industry are manifold no organized attempt to study its effects on reservoir behavior has been made, whereas consideration of clay as a oil source rock has been dealt with exhaustively (29).

7. *Classification of Sediments*

It is patently obvious that methods of classifying sedimentary rocks are not satisfactory; they are generally based on grain size or field occurrence, and rarely bear any relation to rock genesis or composition except in the broadest sense. A classification somewhat analogous to that for igneous rocks and with definite implications with regard to source, genesis and composition has been recently suggested by Krynine (13, 14) and this basis of classification appears to be the most promising so far advanced in regard to sedimentary rocks.

8. *Genesis, Diagenesis, Sedimentation, and Palaeogeography*

These somewhat inter-related studies are singularly unbalanced in their development. They all contain considerable latitude for imaginative reasoning and despite considerable descriptive literature they represent subjects in which the data have outmoded the interpretation or the interpretation has proceeded beyond the limit justified by the observational data. Particulate studies of sediments in regard to size, shape, roundness and mineral composition have led to the impasse that no parameter appears to be characteristic of a particular sediment or environment of deposition (30, 31). The study of sedimentation, despite a large

literature, has failed so far to offer any sign of a revolution in the interpretation of older deposits in terms of the recent. Palaeogeographical reconstruction has in most cases been forced with too little data to support its contentions and so despite considerable philosophizing no convincing solution has appeared to explain source, method of deposition, diagenesis or history of the typical sediment.

IV. CRITICISMS OF APPROACH

The general approach to sedimentary petrography is *via* the classical teaching of the allied subjects igneous and metamorphic petrography. However, there is an outstanding contrast with these two subjects when the descriptive material is reviewed. One of the most exhaustive descriptive texts is Johannsen's 4 volume treatise on the Petrography of Igneous Rocks (8) and, while there is no single work of similar type in the metamorphic field, Van Hise classical text (33) is a close approach and there exist large numbers of purely descriptive publications on this subject.

Compare or rather contrast these descriptions with the standard texts on sedimentary petrography (1, 2, 4, 9, 17, 28, 30) and it will immediately be seen that while techniques, methods of attack and description of the accessory minerals is attended to in all cases, only in Milner's textbook (17) is there any real attempt at petrography of sediments proper. Furthermore any attempt to pursue the subject further and construct a series of descriptive texts for oneself proves abortive. There are, it is true, a small number of excellent and detailed accounts of sedimentary rocks but they have to be searched for very diligently and when compared in amount with their sister subjects, igneous and metamorphic petrography, they make a very poor showing indeed.

One of the more obvious reasons for this lack of descriptive material can be attributed to the difference in age of sedimentary as compared with igneous and metamorphic petrography (60 years as compared with 110 years respectively). Again it is quite common for a graduate to write a thesis for Master's or Doctor's degree on the petrography of an igenous or metamorphic rock (or complex) but it is very rarely that a similar course is followed for a sedimentary rock (or complex). There are many reasons for this, among which may be cited the fallacious statement that the sedimentary rock is poor in minerals when compared with the igneous, or again the description of a sedimentary rock is generally considered exhaustive when the field geologist has examined the rock with the hand lens. The result, of course, has been cumulative—the less one knows about sediments the more simple they appear to be, and the less need there is to know anything about them.

Examine the procedure followed by a geologist when field mapping; usually when mapping an igneous rock the geologist will classify the outcrop broadly and collect samples which will be analyzed very carefully by a competent expert, usually a petrologic or petrographic specialist. Similarly in the case of a metamorphic rock he submits to expert opinion. Now in the case of the sediment he very carefully collects the fossils and follows the same procedure, but the rock, he considers himself adequately qualified to describe macroscopically and beyond that he takes no further interest. To a large extent this is the fault of the sedimentary petrographer who has still to show that he can obtain from the rock any information of use to the geologist or himself. This is again due to the paucity of descriptive work on sediments and perhaps even more so to the superabundance of petrologic philosophy based on very little observation. It is indeed much easier to philosophize on the basis of a few observations than on the more substantial foundation of an exhaustive analysis.*

* The author is under no misapprehension but freely admits that he has committed all or nearly all the errors described in this review.

In summary then it appears that two fundamental criticisms are outstanding to explain the lack of co-ordination in the field of sedimentary petrography, the one is the unbalanced nature of the investigations and the other the lack of detailed and thorough descriptive data on type rocks. One further remark may be made, namely, that the tendency to theorize and philosophize in advance of the observational data has led to many failures which would not exist had the subject been given time to mature before being applied to field problems.

V. RECOMMENDATIONS

This review would not be complete without an attempt to find a solution to the problem even if by so doing the author has to face similar criticisms to that outlined above; hence the following recommendations are put forward:

a) Emphasis should be placed on petrographic observational data and avoidance of petrologic discourse until sufficient information has been compiled to warrant a philosophy.

b) Compilation of the existing data on the petrography of sediments in an easily accessible form (series of mimeographed reports or a symposium).

c) Research projects for M.Sc. and Ph.D. theses by university students on detailed petrography of sedimentary rocks.

d) Research project undertaken by A.A.P.G. Research Committee and/or the U. S. National Committee on Sedimentation along these lines.

e) Petrography of reservoir rocks under a research project with support from petroleum industry (an A.P.I. project, cp. Origin of Oil etc.).

f) Alignment of core analysis and particularly its interpretation in terms of petrographic constitution of the reservoir rock.

The immediate aim of such programs should be to describe in detail one or two rock types from each pigeonhole in the Krynine Classification System as a basic foundation to the general petrography of sediments.

The results of such programs could be published in the *Journal of Sedimentary Petrology* and as Committee on Sedimentation Reports (cp. Accessory Minerals of Igneous Rocks Report (35)).

There is no doubt that a compilation of existing information into one integrated whole (15, 20) would indicate the embayments in the advancing front of knowledge on the petrography of sedimentary rocks and point the direction to future work in this field. In addition it would supply some basic information needed for the application of sedimentary petrography to petroleum industry problems such as location of stratigraphic traps, and reservoir behavior and research.

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COMMITTEE WORKING ON A NEW ROCK-COLOR CHART FOR FIELD USE

A committee representing a number of geological societies and organizations has begun work on a new rock-color chart designed specifically for field use. The membership of the committee is as follows:

Parker D. Trask, representing the Geological Society of America.

Ronald K. DeFord, representing the American Association of Petroleum Geologists.

Joseph T. Singewald, Jr. and R. M. Overbeck, representing the Association of American State Geologists.

Olaf N. Rove, representing the Society of Economic Geologists.

E. N. Goddard, representing the U. S. Geological Survey.

The first meeting of the committee was held on May 2, 1946, in Washington, D.C. Hugh D. Miser, of the Geological Survey, who had been instrumental in getting the work started, gave a brief account of the discussions and correspondence that led up to the organization of the Committee. Mr. DeFord, who was unable to attend, sent a letter suggesting a general plan of procedure, and this letter was used as a basis for discussion. The following plans were agreed upon by the committee.

1. The rock-color chart is to be based on the Munsell color system, the most widely accepted system of color identification in the United States.

2. Simple color names of the ISCC-NBS (Inter-Society Color Council-National Bureau of Standards) method are to be used on the chart, insofar as is applicable to field use. This method has already been adopted by a large number of societies and organizations interested in color.

3. In addition to the color names, the Munsell hue, value and chrome designations are to be put on the chart, for the use of any geologists who feel the need of numerical designations and fine color distinctions.

4. Sedimentary, igneous and metamorphic rocks (both consolidated and unconsolidated) are to be included, and also well cuttings. If possible, both wet and dry rocks are to be included.

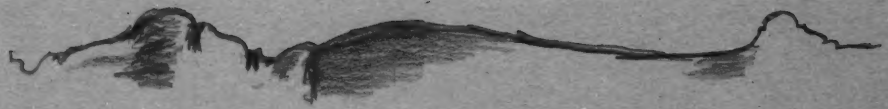
The committee is now engaged in collecting and classifying the widest possible range of rock specimens in order to determine the range of colors needed on the chart. The next meeting of the committee is to be held at the Chicago meetings of the Geological Society of America in December, 1946, and at that time, the following problems will be considered:

1. The number and range of colors, and the appropriate names to be used on the chart.

2. The shape, size and arrangement of the chart, the size of the color tabs, and whether holes in the chart should be used to facilitate comparisons with rock samples.

3. The method and means of printing and distributing the chart.

The committee will welcome any suggestions. The Munsell color system, as applied to rock colors, is discussed by DeFord—Rock Colors: American Association Petroleum Geologists Bulletin, vol. 28, no. 1, pp. 128–137, January 1944. The ISCC-NBS method of naming colors is described by Dean B. Judd and Kenneth L. Kelly—Method of Designating Colors: National Bureau of Standards Research Paper No. 1239, September 1939.



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